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**SUPERCONDUCTING RADIO FREQUENCY TECHNOLOGY:
EXPANDING THE HORIZONS OF PHYSICS
AND TECHNOLOGY**

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1. Introduction

Accelerators have evolved in distinct stages through the development of pioneering concepts and supporting technologies. Each conceptual breakthrough has led to a new generation of machines whose performance significantly outstrips that of previous machines. The concept of electrostatic acceleration, for instance, made possible the first accelerator. Later, the concepts of phase stability, strong focusing, colliding beams, and beam cooling supported major advances in accelerator performance. In parallel with these conceptual developments, new technologies have emerged to make possible accelerators based on the pioneering concepts. The development of radio-frequency acceleration, successfully applied in Ernest Lawrence's 11-inch cyclotron, was the first step in overcoming the energy limit of electrostatic machines. Other examples include high-power rf sources, ultrahigh vacuum capability, computer modeling of beam dynamics, liquid helium cryogenics, and increasingly precise and cost-effective engineering. Today's superconducting accelerator magnets allow multi-tesla bending fields, and thus the achievement of higher particle energies in circular machines of any given size. The Tevatron at Fermilab is now operating as a 900 GeV on 900 GeV proton-antiproton collider in the same tunnel (2π km circumference) built for the 200-GeV Main Ring. The U.S. proposal for the Superconducting Super Collider (SSC) envisions providing 40 TeV in the center-of-mass of colliding protons, using 6.6-tesla magnets in a ring 83 km in circumference. CERN is considering a Large Hadron Collider (LHC) which would achieve center-of-mass collision energies of 16 TeV with ~ 10 -tesla magnets in the 27-km LEP tunnel.

This paper describes a major new technology supporting the further evolution of accelerators: superconducting radio frequency (SRF) technology, which is today on the verge of large-scale application in accelerators. Originally foreseen in the early 1960s as a promising technology [1,2,3], SRF only recently has overcome several technological and practical hurdles. SRF accelerating structures promise low rf losses and high gradients under cw operation. High-quality, intense cw beams can be accelerated without risk of melting the structure and without requiring enormous amounts of input rf power.

The intrinsically low rf losses make SRF technology attractive for high-energy electron-positron storage rings and colliders, TeV-scale electron-positron linear colliders, free electron laser drivers, and all types of cw linacs. Fundamental limits for accelerating gradients are ~ 60 and ~ 100 MV/m for accelerating cavities made of niobium and Nb_3Sn , respectively. Intense R&D efforts supporting cavity development and accelerator design for all these applications have

made significant progress during the past few years. Thus, in 1985, SRF technology was adopted for use in the Continuous Electron Beam Accelerator Facility (CEBAF) [4]. As a 4-GeV, 200- μ A, cw electron accelerator for nuclear physics, CEBAF will use 200 m of accelerating structure and become the first large-scale application of the technology.

This paper covers the recent progress in SRF, describes some present and proposed SRF accelerator projects, and treats briefly the optimization of cryogenic temperature.

2. Radio Frequency Superconductivity

Superconducting rf accelerating structures produce with very small resistive losses the electric field that accelerates the particle beam. Structures have been developed both for low-beta and for $\beta=1$ applications. Until recently the achievable fields were limited to low values (~ 2 MV/m) by multipacting. Moreover, the current-carrying capacity of superconducting accelerators was limited by the intrinsically high Q of higher order modes (HOM), or, in other words, the long lifetime of disruptive transverse and longitudinal resonances of the structure.

After the concept of a superconducting accelerator emerged in the early 1960s, Schwettman's group at Stanford's High Energy Physics Laboratory (HEPL) moved rapidly to develop superconducting accelerating cavities for $\beta=1$ particles, and to build a recirculating electron linac for nuclear physics [5]. Construction started in 1964, and the completed superconducting accelerator (SCA) delivered beams of remarkable quality and stability (Table 1). In 1976 the SCA provided the electron beam for the first successful free electron laser [6].

HEPL's SCA was a pioneering machine. It provided a proof of principle for SRF accelerators. However, multipacting prevented its cavities from achieving gradients above ~ 2 MV/m, far below the hoped-for ~ 20 MV/m. Beam intensity was limited to a few μ A in multipass operation, due to multipass beam breakup as a consequence of poor HOM damping.

Table 1
Electron Beam Parameters of Stanford's SCA* [5]

Energy	44 MeV
ΔE	15 keV ($\sim 0.03\%$)
Peak current	up to 500 μ A
Emittance	0.02 π mm mr
Normalized	1.7 π mm mr
Energy stability	$\sim 10^{-4}$
Position stability	< 0.1 beam size

*Single-pass operation during the 1970s.

In parallel with HEPL's construction, efforts to develop low-beta resonators were initiated at Karlsruhe, Caltech, and Argonne. In 1972, construction of the first superconducting heavy-ion linac using these structures was started at Argonne National Laboratory [7]. It began operation in 1978 as a post-accelerator for Argonne's tandem Van de Graaff. Subsequently several other low-beta superconducting linacs have been built to increase the energy of heavy ions produced by Van de Graaffs [8].

Major R&D efforts have been conducted at Stanford, Karlsruhe, Cornell, CERN, DESY, Wuppertal, Orsay, and KEK to develop improved $\beta = 1$ superconducting rf structures [9]. Recent improvements have allowed gradients in multicell cavities to exceed 5 MV/m routinely. Gradients in single-cell cavities between 15 and 20 MV/m are becoming common.

Reasons for improved performance are the following:

- spherical or elliptical cell shape to reduce multipacting (Figure 1),
- improved fabrication and processing methods to minimize defects and surface impurities,
- thermometric mapping to locate hot spots caused by field emission or by defects or dirt on the superconducting surface,
- improved thermal conductivity of niobium to stabilize microscopic defects against driving the cavity normal (Figure 2),
- improvement in welding techniques to avoid spatter and vacuum bubbles in welds,
- beam-pipe couplers to minimize field enhancement, and
- computer codes (e.g., URMEL [10]) to visualize field patterns that may be helpful in the still largely empirical design of couplers.

In addition, titanium or yttrium gettering can remove interstitial oxygen from the niobium, thereby improving the thermal conductivity [11, 12]. Either treatment can be applied to whole cavities or to cell cups prior to welding. The titanium treatment has achieved the lowest residual surface resistance (highest residual Q) on record ($1.6 \times 10^{-9} \Omega$ at 1500 MHz) [13].

Multicell $\beta=1$ cavities today have been built at several frequencies between 350 MHz and 3.0 GHz. Design parameters currently achievable by industry are an accelerating gradient of 5 to 10 MV/m and a Q in the range 2.5×10^9 to 4×10^9 . These parameters make SRF technology economically viable for use in medium-energy and recirculating electron linacs for nuclear physics, for free electron laser drivers, and for high-energy electron-positron storage rings and colliders. For economical application of SRF in very large scale projects, such as TeV-scale linear colliders, improved performance is necessary. Thus, R&D focuses on achieving gradients of 30 MV/m.

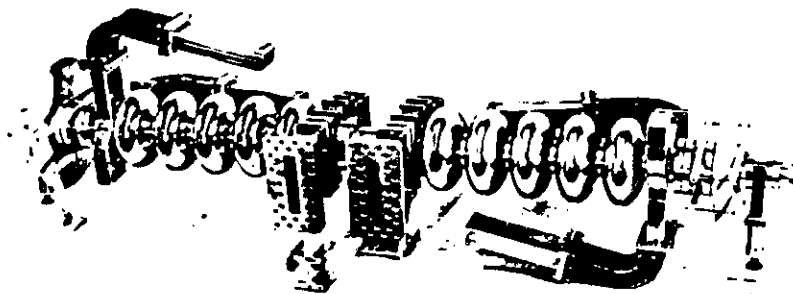


Figure 1 An assembled pair of CEBAF superconducting cavities, developed at Cornell University's Newman Laboratory of Nuclear Studies. Each cavity has five elliptical cells.

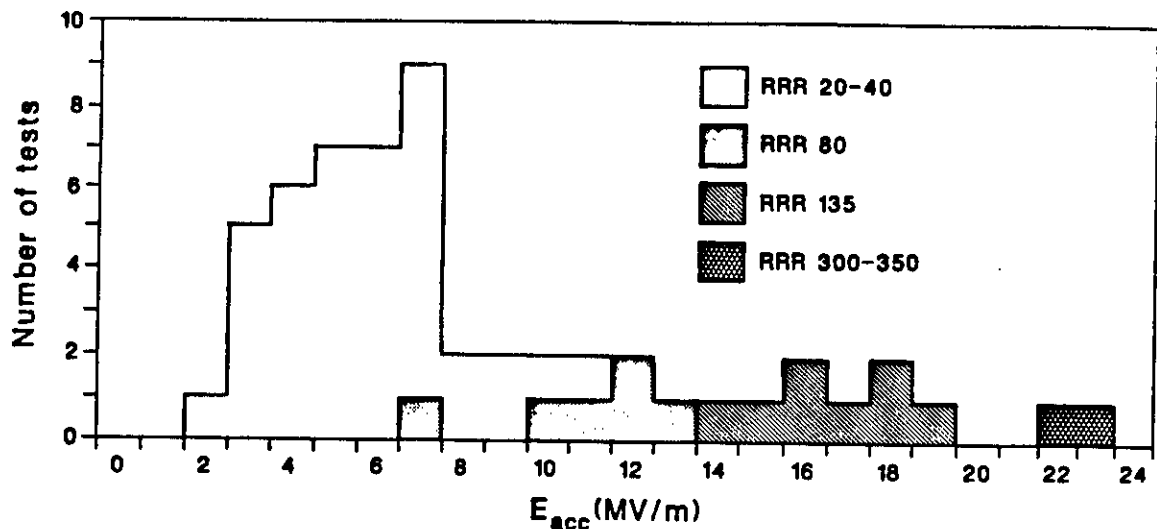


Figure 2 Gradient improves with niobium thermal conductivity in single-cell superconducting cavities. $RRR = \frac{\text{resistivity at 300 K}}{\text{resistivity at 4.2 K}}$. (Source: H. Piel, Wuppertal.)

3. SRF Accelerators Proposed and Under Construction

Electron-Positron Storage Rings

Three laboratories (CERN, DESY, and KEK) are developing cavities and designs based on SRF technology for upgrades of high-energy electron and/or positron storage rings (Table 2). The technology is attractive because SRF cavities provide greater energy gain per turn than can be achieved with copper structures, and they permit the radiated energy to be replenished using an affordable amount of rf power. Since synchrotron radiation losses increase with the fourth power of beam energy in a circular machine, maintaining the beam energy using copper cavities becomes impractical as the beam energy increases.

Table 2
Application of $\beta=1$ Superconducting Cavities
Storage Rings

Laboratory	Accelerator	Frequency (MHz)	Active length (m)
CERN	LEP Stage II (77 GeV)	350	110
	LEP Stage III (92 GeV)	350	330
DESY	HERA e (30 GeV)	500	20
KEK	TRISTAN (33-35 GeV)	508	60
	TRISTAN (40 GeV)	508	180-216

One of the proposed SRF applications is in the LEP electron-positron collider for high energy physics, currently under construction in a 27-km tunnel at CERN. LEP's initial design energy is 55 GeV, to be reached and maintained with copper cavities. CERN's plans call for upgrading LEP in two stages by adding and substituting superconducting niobium or niobium-on-copper cavities in the accelerating sections (Table 3). LEP's four-cell cavities operate at 350 MHz. The

design gradient is 5.0 MV/m minimum with 7.0 MV/m expected, as compared with 1.5 MV/m expected from the copper cavities. The design Q_0 is 3×10^9 at the operating temperature of 4.2 K. To gain experience with the superconducting cavities, CERN plans to install one in the SPS in summer 1987, and to include four in LEP's Stage I.

Table 3
Proposed LEP Upgrades [14]

Stage	Number of cavities	Gradient (MV/m)	Beam energy (GeV)
I	128 Cu + 4 SC	1.5/5.0	55
IIA	128 Cu + 32 SC	1.5/7.0	67
IIB	128 Cu + 64 SC	1.5/7.0	77
III	192 SC	7.0	92

Electron Linacs

At HEPL, the SCA has been operating since the mid 1970s. Currently it is being converted into an FEL facility to provide photons of wavelength 0.5 to 15 μm [15]. A small recirculating linac at the University of Darmstadt (Federal Republic of Germany) is being commissioned, and a large recirculating linac at CEBAF in Newport News, Virginia, is currently under construction. Saclay (France) has proposed to build a superconducting recirculating linac in the 1.5- to 3-GeV range for nuclear physics applications. Italy, currently formulating a five-year plan, is considering building a multi-use recirculating superconducting linac facility that in its first stages would provide beams for FELs and for nuclear physics. Subsequent additions of damping rings and a larger recirculating linac complex could access charm, tau, and beauty physics [16]. Table 4 lists the electron linacs currently in design or under construction. The following paragraphs describe the Darmstadt, CEBAF, and Saclay accelerators and their current status.

Table 4
Application of $\beta=1$ Superconducting Cavities
Linacs

Laboratory	Accelerator	Frequency (MHz)	Active length (m)	Status
Darmstadt	130-MeV linac	3000	12	In commissioning
CEBAF	4-GeV linac	1500	200	Construction
Saclay	ALS-SUPRA	1500	140	Design
INFN (Italy)	Recirc. linac	~ 500	~ 100	Under discussion
Stanford/TRW	FEL driver	1300/500	5-6	Construction
?	TeV linear collider	$\sim 1000-3000$	$\sim 8 \times 10^4$	Speculative

Darmstadt's electron accelerator is a three-pass linac, designed to deliver 20- μA cw beams at energies up to 130 MeV with an energy spread of 10^{-4} for low-energy coincidence experiments for nuclear physics [17]. The machine is based on 20-cell, 3-GHz niobium cavities developed

at Wuppertal. Cavity performance specifications at the operating temperature of 1.8 K are a gradient of at least 5 MV/m and a Q of 3×10^9 .

Figure 3 shows the Darmstadt machine layout. Electrons from a 250-kV gun are bunched, chopped, and accelerated by an injector accelerator consisting of a short (5-cell) superconducting, $\beta=1$ structure followed by two of the 20-cell cavities. The 10-MeV beam is then injected into the 40-MeV main linac. This linac contains eight 20-cell cavities, four each in two cryostats. Two recirculation beam lines return the beam for up to three passes through the main linac. By spring 1987, an electron beam had been accelerated through two phase-locked superconducting structures in the injector.

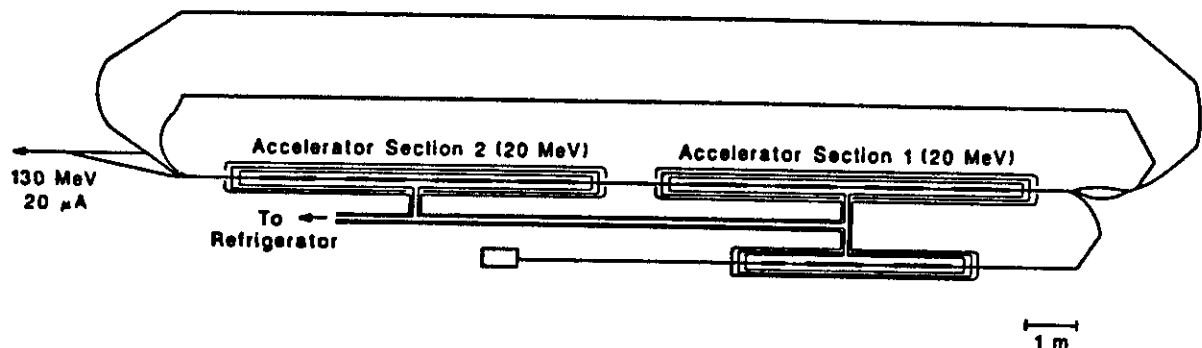


Figure 3 Layout of 130-MeV superconducting recirculating linac, Darmstadt.

In Saclay, France, the ALS SUPRA has been proposed to replace the ALS pulsed linac [18]. Current plans call for constructing the machine in stages, with ~ 500 to ~ 700 MeV cw beams available by 1992, 1.5 to 2 GeV by 1993, and 3 to 6 GeV still later. The design current is $100 \mu\text{A}$. The construction project has yet to be approved and funded, but cavity R&D is in progress. Saclay has selected 1500 MHz as the rf frequency, and anticipates a minimum accelerating gradient of 7 MV/m. Stage I includes 70 m of active length in single-pass operation. Stage II involves building two recirculation paths. The possible future addition of a second linac (Stage III), antiparallel to the first, with additional recirculation paths, would allow energies as high as 6 GeV to be achieved. Figure 4 shows these plans schematically.

On February 13, 1987, construction started on the Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, Virginia. The 4-GeV, $200\text{-}\mu\text{A}$, cw electron accelerator (Figure 5) will have two antiparallel, 500-MeV, superconducting linacs connected by beam lines to allow up to four passes of recirculation [4]. The accelerating structure consists of 1500-MHz, five-cell niobium cavities (Figure 1) [19]. Ten prototype cavities have been fabricated by industry. Tests of the prototypes confirm that the design gradient of 5 MV/m and the design Q_0 of 2.4×10^9 at the operating temperature of 2 K are achievable.

Current linac projects require multiple recirculation, which allows a high energy to be reached with a comparatively modest length and cost of linac. In addition, it is possible to deliver to a few (n) simultaneous experiments beams of different, but correlated, energies. Extraction takes place by removing every n th bunch after the first, second, ..., or final pass. Thus each experiment receives a beam with a frequency that is a fraction ($1/n$) of the fundamental rf frequency. Choice of fundamental rf frequency must account for the fact that the delivered beam can be effectively cw only if its frequency is too high for the detectors to see the individual rf pulses. Both Saclay and CEBAF selected 1500 MHz to assure that the delivered beam is at least 500 MHz.

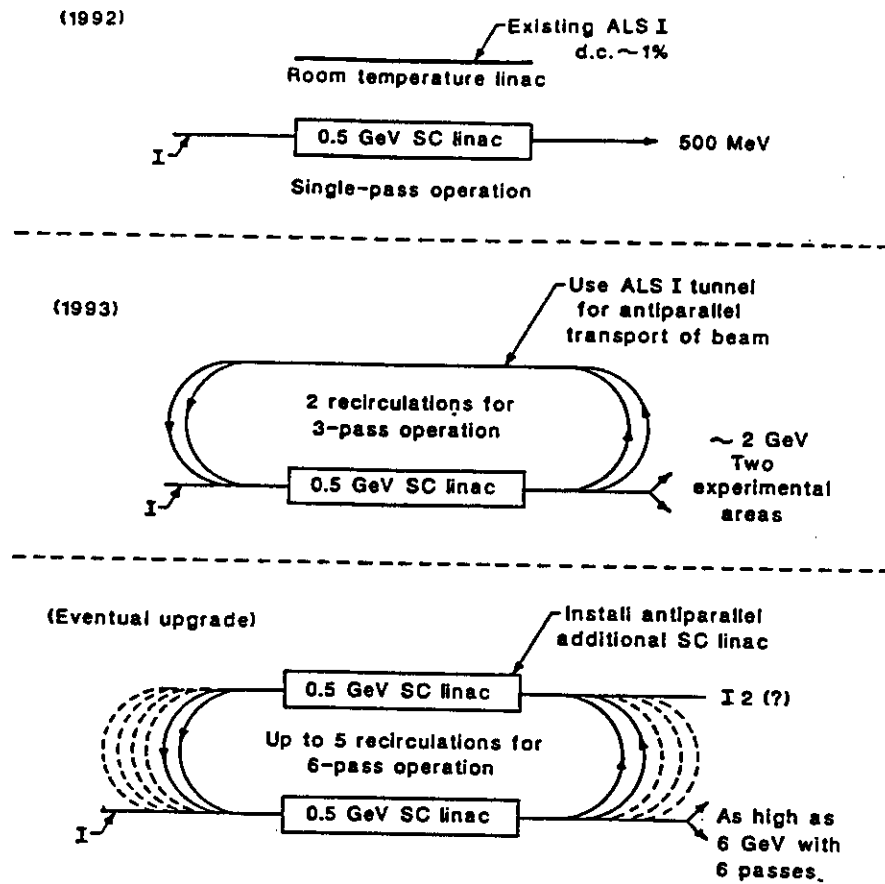


Figure 4 Proposed evolution of ALS SUPRA, Saclay.

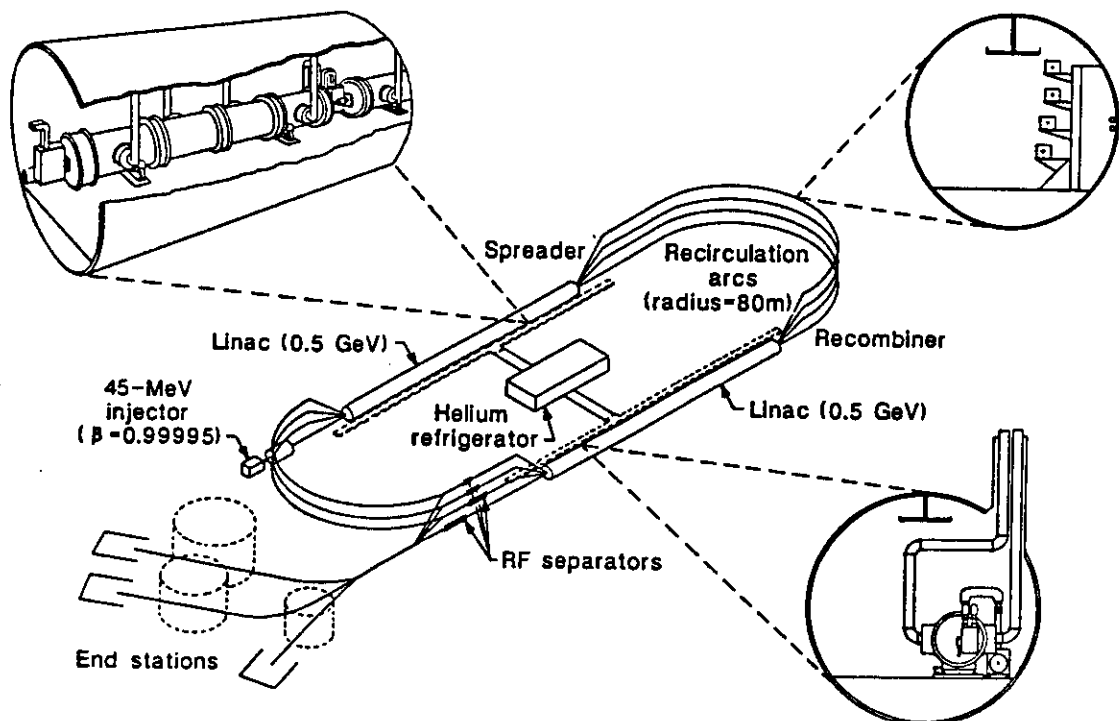


Figure 5 Layout of the CEBAF 4-GeV superconducting recirculating linac, Newport News, Virginia.

Recirculating a beam through a linac, however, can produce a transverse instability due to the excitation of HOMs. The recirculated beam and cavities form a feedback loop which can be driven unstable at sufficiently high currents. This multipass beam breakup can severely limit current in a recirculating superconducting linac, due to the intrinsically high Q and long lifetime of the HOMs. Superconducting cavities must be carefully designed to damp HOMs. For the cavity design adopted for CEBAF [19], analytical modeling and numerical simulations indicate that CEBAF's design current is two orders of magnitude below the beam breakup threshold [20].

Free Electron Laser Drivers

Free electron lasers (FELs) have several advantages as light sources. They can provide photon wavelengths tuneable over a broad range, high beam power and efficiency in a controllable pulse structure, and high spectral brilliance.

The essential components of an FEL are a low-emittance high-current electron beam and an undulator or tapered wiggler to stimulate coherent photon emission from the beam. FELs can operate in an oscillator mode or in a single-pass mode. In the single-pass mode, the FEL beam is produced directly on one pass of the electron beam through the undulator or wiggler by the interaction of the electron beam and photon beam as they traverse the device together. In the oscillator mode, mirrors are used beyond each end of the insertion device to allow multiple reflections of the photon beam and thus its amplification via superposition with photons emitted by later electrons and by repeated interaction with the electron beam.

RF linacs can provide beams meeting or exceeding the requirements for FELs (Table 5). Output beam quality is most strongly determined by electron gun and preaccelerator performance, although attention to collective effects is essential throughout the whole acceleration process. For FELs with very low macroscopic duty factor, the high gradients achievable with copper cavities may be attractive. For higher duty factors (and therefore higher average beam power) and, in particular, for cw operation, SRF technology allows higher gradients, lower power consumption, and offers the possibility of beam energy recovery. Furthermore, in SRF technology there is less of a penalty associated with low frequencies (\sim a few 10^8 Hz), and therefore substantially lower impedances for HOMs. Thus SRF technology seems to hold a natural advantage for the achievement of very high currents ($\gtrsim 1$ kA) [21].

Table 5
Beam Requirements for Free Electron Lasers [21]

Energy	$\lesssim 1.0$ GeV
Normalized emittance (rms)	~ 1.0 μm
Peak current	$\gtrsim 100$ A
Energy spread (rms)	$\lesssim 125$ keV

The first successful FEL used the electron beam from HEPL's SCA [6]. Currently Stanford and TRW are collaborating to convert the SCA into an FEL facility with energy recovery.

Linear Colliders

Synchrotron radiation losses make it highly impractical to produce e^+e^- collisions at very high center-of-mass energy using storage rings. Linear colliders provide an alternative [22]; thus groups at CERN, Cornell, SLAC, KEK, and elsewhere are developing linear-collider approaches for accessing the TeV mass region with a luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Two approaches conceived to date rely on SRF technology, either in the linac itself or in a drive linac [23].

Fully superconducting linacs have three advantages over normal conducting linacs: (1) The high cavity Q permits rf power to be supplied slowly, thereby keeping peak power requirements well within current technological capability. (2) Superconducting structures operating at 1000–3000 MHz have acceptable power dissipation and transverse impedance. Tolerances and beam dynamics issues are much less severe than in the 10-to-30-GHz range required for normal conducting linear colliders. (3) The primary issue related to constructability is cost, which imposes minimum requirements on gradient and Q . Gradients in the neighborhood of 30 MV/m—a five-fold to sixfold improvement over industrial capability today—bring the capital costs of a fully superconducting linear collider into the few-billion-dollar range. For cw operation, a simultaneous improvement in cavity Q to $\sim 9 \times 10^{10}$ would be necessary. Alternatively, the duty cycle of the linear collider could be reduced, thereby eliminating the need to exceed Q 's presently obtainable [24].

An alternative, partially superconducting, approach uses a cw, low-frequency (300–500 MHz) SRF drive linac coupled to a high-frequency (30 GHz) normal conducting main linac [23]. Gradient requirements on the drive linac are moderate (5–15 MV/m). Energy recovery is possible. The key factor is efficient energy transfer to the high-energy beam, which requires excellent energy spread in the drive linac.

Heavy Ion Superconducting Booster Linacs

Superconducting linacs have been installed as post-accelerators at tandem Van de Graaffs. The accelerating structures are low-beta resonators of various designs that operate in the frequency range between 100 MHz and 200 MHz [25]. This technology and the resonators were pioneered in the 1970s by Karlsruhe, Caltech, and Argonne. In 1970, Karlsruhe achieved the first operation of a niobium low-beta helix resonator [26]. Two years later they accelerated the first ion beam with a superconducting structure [27].

Both niobium and lead-on-copper resonators have been used. Lead-on-copper structures are inexpensive to manufacture; however, they have higher rf losses than niobium, so they are more expensive to operate. Typically field emission has limited the achievable gradient of both types of resonators to 3 to 4 MV/m.

In a superconducting low-beta linac, the particle's velocity increases significantly as it is accelerated. Thus each resonator along the linac must be matched to the beta of the particle entering that resonator. Table 6 lists superconducting heavy-ion booster linacs currently operating or under construction.

Table 6
Heavy Ion Superconducting Booster Linacs (low β) [8]

System	Superconductor	Resonator type	f_{rf} (MHz)	Active length (m)	Number of resonators
ANL ATLAS	Nb	split ring	97	13.3	42
SUNY Stony Brook	Pb	split ring	150	7.5	40
Weizmann Institute	Pb	quarter wave	162	0.7	4
Saclay	Nb	helix	135	12.5	50
Florida State	Nb	split ring	97	4.5	13
Oxford	Pb	split ring	150	2.1	9
U. of Washington	Pb	quarter wave	150	8.6	36
Canberra	Pb	quarter wave	150	0.8	4
Kansas State	Nb	split ring	97	3.5	16

4. Cryogenic Temperature Optimization

Temperature optimization is both a cost and performance issue for SRF accelerators. Cavity performance improves and rf losses decrease as operating temperature is lowered. However, both cryogenic complexity and operating power per cryogenic watt increase as temperature is lowered. Figure 6 shows the effect of the two factors schematically.

Where the cost minimum actually falls depends on design details of the cavities, predominantly their material and their resonant frequency. BCS Q decreases with the square of the operating frequency. Thus low-beta structures (100–200 MHz) can operate at 4.2 K to 4.5 K, as can the cavities being developed for CERN (350 MHz) and DESY (500 MHz). CEBAF's temperature optimum falls close to 2.0 K, due to its frequency of 1500 MHz. Darmstadt, at 3000 MHz, has selected an operating temperature of 1.8 K.

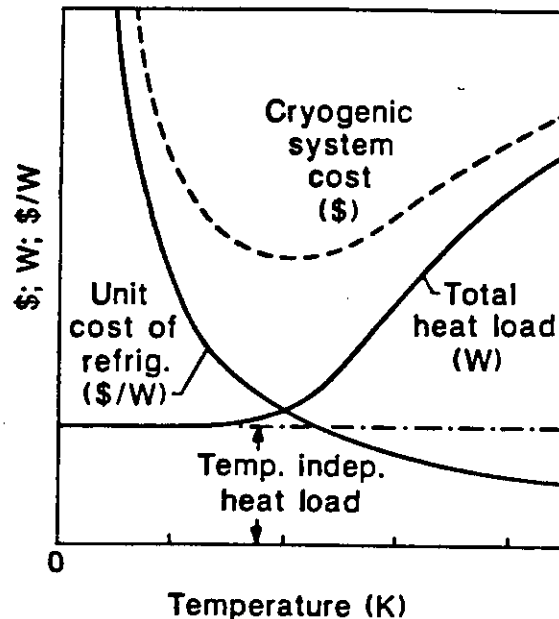


Figure 6 Generic cost optimization of cryogenic systems for SRF accelerators. The ordinate is a linear scale for the cost variables, and logarithmic for heat load. The abscissa is a linear temperature scale.

Fairly large liquid helium refrigerators are operating or are being commissioned at many laboratories (Table 7). The critical component for achieving temperatures at or below the lambda point is the cold compressor, which recently has been the subject of successful R&D. Thus cryogenic issues associated with superconducting rf accelerators are important but resolvable.

Table 7
Large Liquid Helium Refrigerators

	Temperature (K)	Unit capacity (kW)	# of units	Status
Tevatron	4.5	29	1(+29)	Operational
BNL	4.3	24	1	Commissioned
HERA	4.35	6.3	3	One commissioned
CEBAF	2.0	4.8	1	Planned
MFTF-B	4.4	10	1	Operational
Tristan	4.4	6.6	1	Planned
MFTF-A	4.4	3.3	1	Operational
Tore Supra	1.8 and 4.0	0.3 0.7	1	Commissioned

5. A Note on the New Superconductors

In principle, application of the recently discovered superconductors with transition temperatures (T_c) above 90 K could reduce the operating cost of SRF accelerators by permitting a higher temperature to be used, thereby reducing the required refrigerator power. It may also be discovered that the superconductors have other properties which make their application to rf cavities desirable. However, two difficulties make today's high- T_c superconductors impractical: (1) They have a low Q and therefore dissipate a large amount of power which must be removed by the refrigeration system. (2) Their chemical stability is poor.

Initial studies have been made of the rf properties of the new superconductors. Samples made by the Los Alamos National Laboratory and the Bergische Universität (Wuppertal) have been evaluated at Wuppertal in the Federal Republic of Germany [28]. It was found that the material has far greater losses than any metal in the normal-conducting state. In the superconducting state, the losses are roughly equivalent to those of copper. In contrast, the niobium presently used in superconducting cavities is capable of yielding losses which are 10^5 to 10^7 times smaller than those of copper. High losses would require that the cryogenic system have a cooling capacity increased by the same factor.

Another important factor in the application of superconductors to rf is the requirement that the operating temperature be well below the superconducting transition temperature. To ensure that a sufficiently large fraction of the conduction electrons are in the superconducting state, it is necessary to have a superconductor at a temperature which is 1/5 to 1/2 of its transition temperature. This requirement substantially lowers the refrigerator efficiency and operating convenience.

There is much to be learned about the new superconductors. The mechanism by which superconductivity occurs in these materials is not well understood, and it appears that the superconductivity is anisotropic. To develop the new, high- T_c superconductors for rf application will require a major R&D effort focusing on many areas. Examples are increasing the Q , developing high purity and homogeneity, developing methods for depositing thin films with excellent surface properties, adhering of the thin film to the substrate, controlling the crystal axis orientation, stabilizing the material in a vacuum (there is evidence that the oxygen is not well bound), improving the critical current density, and controlling secondary emission (to limit multipacting). A few laboratories have already initiated programs to investigate and develop the rf properties of these materials.

6. Summary

Superconducting rf technology is growing very rapidly. A base of experience is building worldwide at accelerator laboratories, at universities, and in industry. The planned application of superconducting structures in several major accelerators and upgrades has increased the technology's visibility and its pace of advance.

In this light, superconducting accelerators today have two important roles: to support physics research, and to serve as a test bed for this promising technology.

References

1. A. P. Banford, "The Application of Superconductivity to Linear Accelerators," *International Advances in Cryogenic Engineering* 10 (1965) 80-87.
2. H. A. Schwettman, P. B. Wilson, J. M. Pierce, W. M. Fairbank, "The Application of Superconductivity to Electron Linear Accelerators," *ibid.*, 88-97.
3. P. B. Wilson and H. A. Schwettman, "Superconducting Accelerators," *IEEE Trans. Nucl. Sci.* June 1965, 1045-1052.
4. H. A. Grunder, *et al.*, "The Continuous Electron Beam Accelerator Facility," Proceedings of the 1987 Particle Accelerator Conference (in press).
5. C. M. Lyneis, *et al.*, "The Superconducting Recyclotron at Stanford," *Proceedings of the Conference on Future Possibilities for Electron Accelerators*, Jan. 8-10, 1979, Charlottesville, Va. (1978) A1-A14.
6. D.A.G. Deacon, *et al.*, *Phys. Rev. Lett.* 38, 892 (1977).
7. K. W. Shepard, "Initial Operation of the Argonne Superconducting Heavy-Ion Linac," *IEEE Trans. Nucl. Sci.* NS-26, 3659-3663 (1979).
8. L. M. Bollinger, *Nucl. Instr. and Meth.* A244, 246 (1986).
9. H. Lengeler, ed., *Proc. 2nd Workshop on RF Superconductivity*, CERN (1984).
10. T. Weiland, DESY Rept. 82-015 (1982).
11. P. Kneisel, Cornell Laboratory of Nuclear Studies, Internal Report SRF-840702, 1984.
12. H. Padamsee, U.S. Patent No. 4,487,637 (1984).
13. P. Kneisel, *Jour. Less Common Metals* (in press).
14. P. Bernard, private communication (1987).

15. T. Smith, "The Stanford Superconducting Linac," in *Proceedings of the Discussion Meeting on S.C. Linear Accelerators*, Frascati, Italy, October 13-14, 1986, S. Stipcich, ed.
16. U. Amaldi, *A Superconducting Radiofrequency Complex for Molecular, Nuclear, and Particle Physics*, CERN-EP/87-104 (1987).
17. K. Alrutz-Ziemssen, H.-D. Gräf, V. Huck, *et al.*, "The Superconducting 130 MeV Recyclotron for Electrons at Darmstadt," *1986 Linear Accel. Conf. Proceedings*, SLAC-Report-303, 512-514 (1986).
18. F. Netter, "The Saclay SC Linac Project," in *Proceedings of the Discussion Meeting on S.C. Linear Accelerators*, Frascati, Italy October 13-14, 1986, S. Stipcich, ed.
19. R. M. Sundelin, "High Gradient Superconducting Cavities for Storage Rings," *IEEE Trans. Nucl. Sci.* NS-32 (1985) 3570-3573.
20. J. J. Bisognano and G. A. Krafft, "Multipass Beam Breakup in the CEBAF Superconducting Linac," *1986 Linear Accel. Conf. Proceedings*, SLAC-Report 303, 452-454.
21. Report of the Working Group on Linac Transport and Acceleration, ICFA Workshop on High Brightness Beams, Brookhaven, March 1987 (in press).
22. M. Tigner, *Nuovo Cimento* 37 (1965) 1228.
23. W. Schnell, "Radio-Frequency Acceleration for Linear Colliders," CERN-LEP-RF/86-27 (1986).
24. R. M. Sundelin, "2 TeV CM e^+e^- Linear Colliders," CLNS 85/709 (1985).
25. L. M. Bollinger, "Superconducting Linear Accelerators for Heavy Ions," *Ann. Rev. Nucl. Part. Sci.* 36 (1986) 475-503.
26. A. Citron, Proc. 1970 Proton Linear Accelerator Conf. FNAL Batavia, Ill., 239-247 (1970).
27. A. Brandelik, A. Citron, P. Flecher, J.L. Fricke, R. Hietschold, *et al.*, in Proc. Proton Lin. Accel. Conf., Oct. 10-13, 1972, 93-97, LASL Rept. LA 5115 (1972).
28. M. Hagen *et al.*, "Observation of RF Superconductivity in $Y_1 Ba_2 Cu_3 O_{9-\delta}$ at 3 GHz," April 1987, Preprint Bergische Universität Gesamthochschule Wuppertal, WVB 87-12.

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